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Sow and Grow on the Nanoscale – Monitoring Bottom-Up Processes by In Situ Transmission Electron Microscopy

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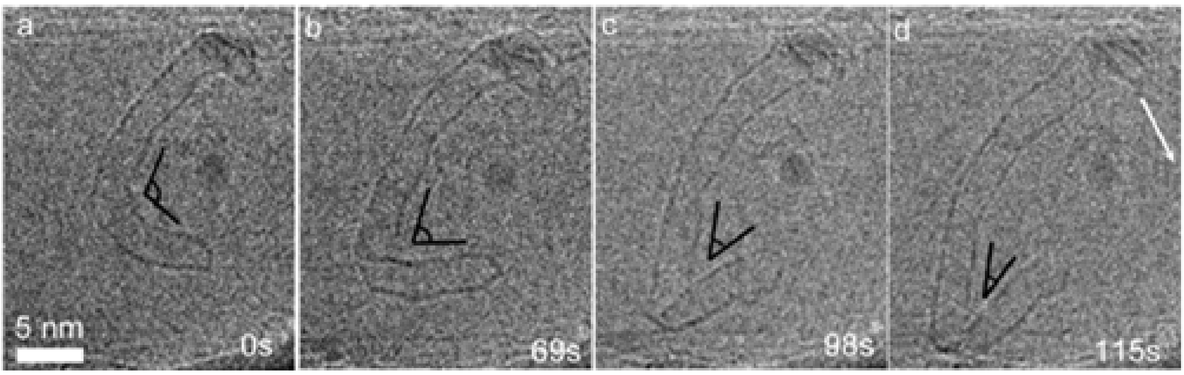
Low-dimensional carbon nanostructures have huge potential for substituting rare metals in electronic devices providing a more environmental friendly fabrication route due to the rich resource of carbon element. However, in order to optimize the synthesis of such tailored carbon based materials, a deep understanding of the formation mechanisms from bottom-up processes is of great importance.

The thermally driven growth of carbon nanotubes (CNTs) is a well-established nanostructure formation process. Single-wall CNTs (SWCNTs) show either metallic or semiconducting behavior depending on the exact geometry of the rolled-up single carbon layer. In order to facilitate large-scale production of CNTs with specific properties, a better understanding of the initial growth from the catalyst particles is essential. Environmental TEM (ETEM) serves a unique way to address the initial and continued growth of individual SWCNTs at the atomic scale under relevant growth conditions [1].



Co/MgO sample exposed to a mixture of CO and H_2 precursor gas (5:2 in mole ratio, totally 760 Pa) at 700˚C resulting in the formation of a SWCNT [2].

The diameter and thereby the chirality of the SWCNTs strongly depends on the access to carbon atoms, which incorporate into the tube securing growth. Changes in the amount of accessible carbon, either by changes in the carbon source supply or by changes in the catalytic cracking of the carbon source to free carbon atoms, strongly influence the growth rate. External forces such as stress will also lead to growth termination, as the incorporation rate of active carbon atoms into the tube is limited. Local variations in the individual SWCNT growth elucidate the importance of an in-depth understanding of the role of catalysts and carbon sources in the continued growth of SWCNTs. Controlling the carbon source accessibility opens for repeated growth of SWCNTs (reuse of catalyst particles) for high growth efficiency.

Here, I will give examples of ETEM used to unravel the growth phenomena and mechanisms of 1-dimensional (SWCNTs) and 2-dimensional (graphene) carbon structures together with machine-assisted analysis of atomically resolved images of such.

[1] M. He *et al.*, Scientific Reports 3, 1460-1466 (2013)

[2] L. Zhang *et al.*, ACS Nano 11, 4483-4493, (2017)